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Strain- and Temperature-Dependence of Electromagnetic Metamaterials

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Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **AUG 2012**	2. REPORT TYPE	3. DATES COVERED **00-00-2012 to 00-00-2012**

4. TITLE AND SUBTITLE **Strain- and Temperature-Dependence of Electromagnetic Metamaterials**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Air Force Research Laboratory,Space Vehicles Directorate AFRL/RVSVS,Wright Patterson AFB,OH,45433**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Presented at the 2nd Multifunctional Materials for Defense Workshop in conjunction with the 2012 Annual Grantees'/Contractors' Meeting for AFOSR Program on Mechanics of Multifunctional Materials & Microsystems Held 30 July - 3 August 2012 in Arlington, VA. Sponsored by AFRL, AFOSR, ARO, NRL, ONR, and ARL.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**14**	

Agenda

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- Analytic Expression for Constitutive Parameters
- Equivalent Circuit Expressions
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- Low Modulus Substrate
- Testing
- Process
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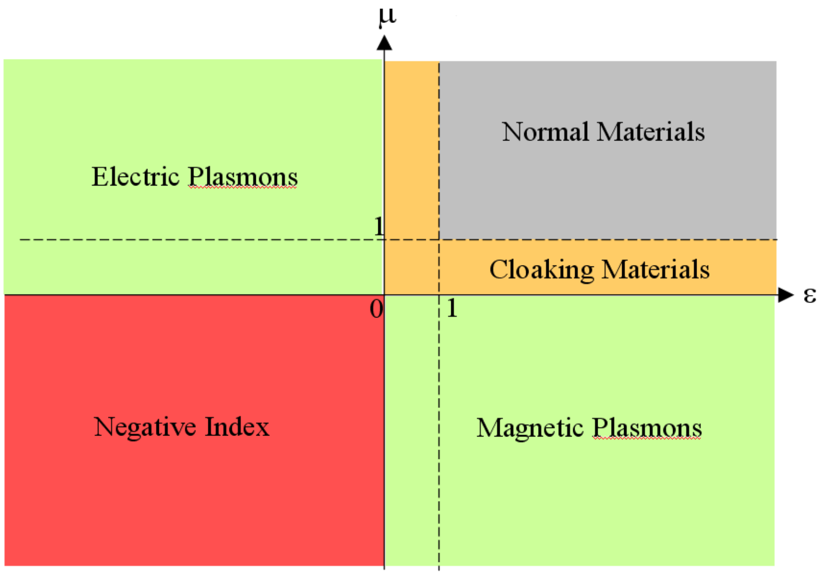
Motivation

- **Tailored EM Response**
  - Engineered Constitutive Props: Permittivity, Permeability, Magneto-electric coupling
  - Frequency-dependent
  - Anisotropic
  - Inhomogeneous
- **Impressive Results: Lab Env.**



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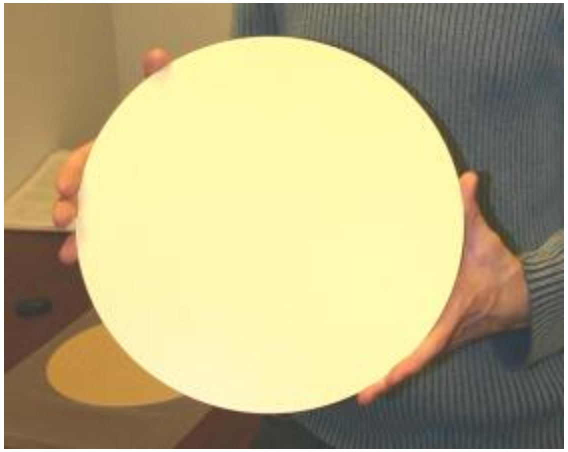
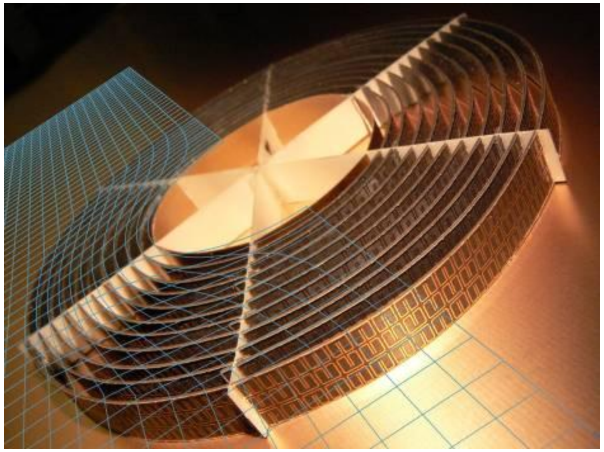


Applied Physics Letters, 88, 081101 (2006)



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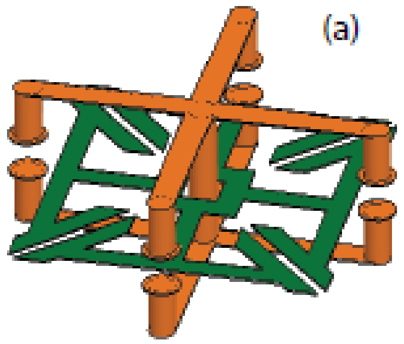


*IEEE Antennas and Wireless Propagation Letters,*8, 1268-1271 (2009)

Motivation

- **Defense Systems Operate in Extreme Environments**
- **Require ability to understand and predict performance before transitioning into Operational Platforms**
  - **Temperature Changes**
  - **Mechanical Loading**
- **Large Structures, Dynamic Environment, Many Unique Unit Cell Designs**




Analytic Expressions for Constitutive Parameters

- **Analytic Expressions for ε and μ**
  - **ELC Unit Cell**
  - **Source is external**
  - **Prediction of full Structure's Performance**

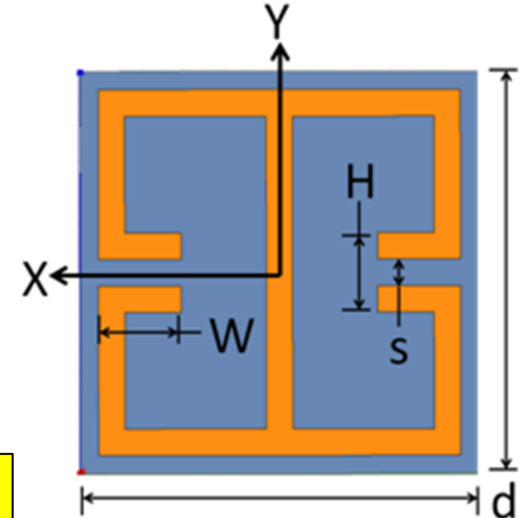
$$\varepsilon = \bar{\varepsilon}\,\frac{\frac{\theta d}{2}}{\sin\frac{\theta d}{2}\cos\frac{\theta d}{2}} \qquad \mu = \frac{\frac{\theta d}{2}}{\sin\frac{\theta d}{2}}\cos\frac{\theta d}{2} \qquad \bar{\varepsilon}(f) = \varepsilon_b - \frac{f_p^2}{f^2 - f_0^2 + i\Gamma_e f}$$

$$\theta = n_{eff}\frac{\omega}{c}$$

- **Alternate Form of the Lorentzian Term**

$$\bar{\varepsilon} = 1 + \frac{C_{ext}}{d\varepsilon_0}\,\frac{\omega_0^2 - \omega^2}{\omega_0^2 - \omega^2\left(1 + \frac{C_{ext}}{C_{int}}\right)} \qquad \omega_0^2 = \frac{1}{LC_{int}} \qquad L = L + \frac{R}{j\omega}$$

$$\sin\frac{\theta d}{2} = \sqrt{\bar{\varepsilon}}\,\frac{kd}{2}$$



Metamaterial's Strain- and Temperature-Dependence can be FULLY described via *R, L, C_{int}, C_{ext}*

Equivalent Circuit Expressions

- **Equivalent circuits expressions are functions of geometry and materials properties**
  - **Mechanical Strain: Change in Geometry**
  - **Temperature Change: Mechanical Strain and Changes in Material Properties**

$$C = C_a + C_s$$

$$C_a = \varepsilon_0 \frac{2}{\pi} \ln\left(2\beta \frac{H}{s}\right) W$$

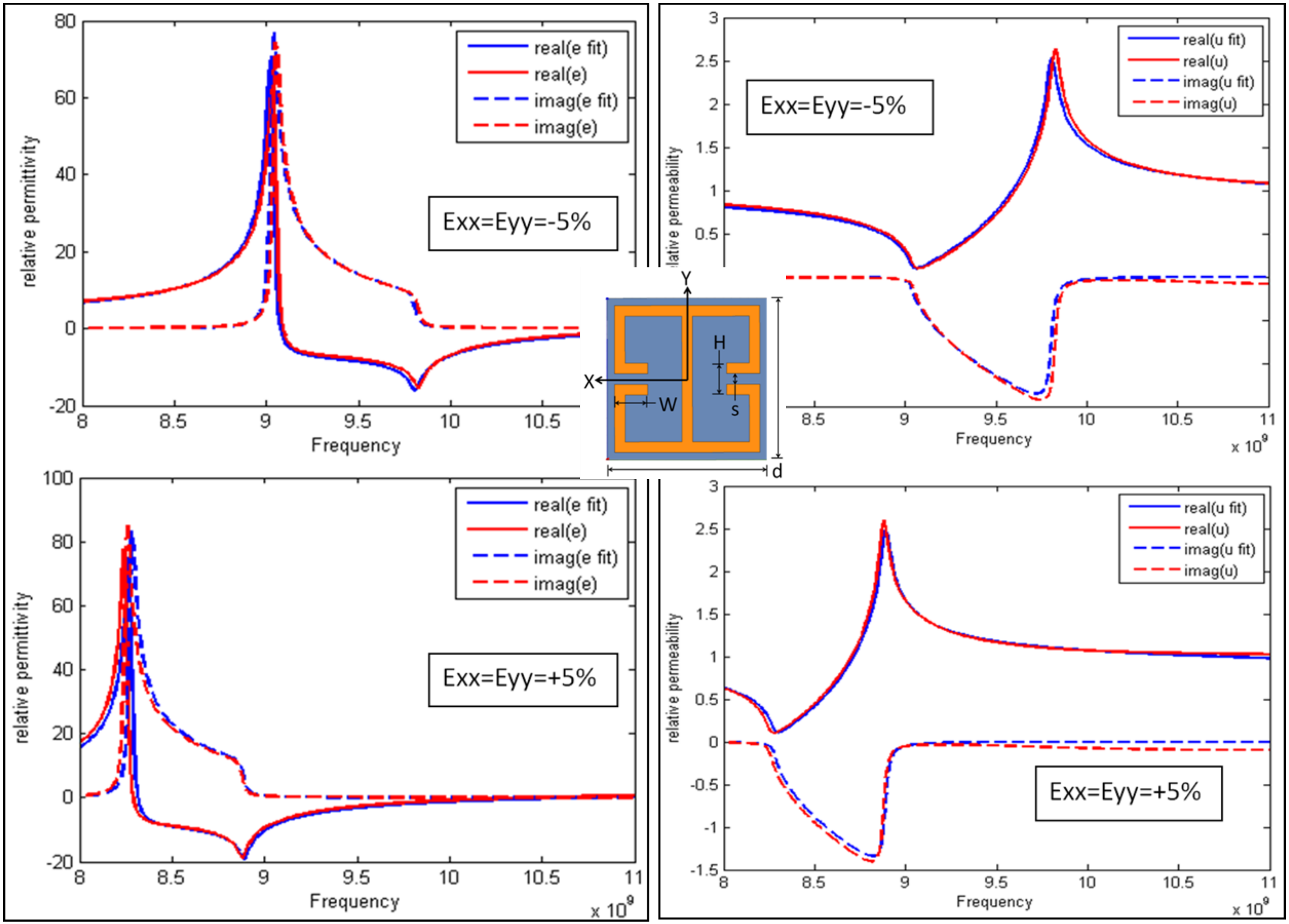
$$C_s = \varepsilon_0 \frac{\varepsilon_s - 1}{\frac{s}{h_s} + \frac{4}{\pi} \ln \beta} W$$

$$L = \frac{\mu_0 l}{2\pi}\left[\ln\left(\frac{2l}{b}\right) + \frac{1}{2} + \frac{b}{3l} - \frac{b^2}{24l^2}\right]$$

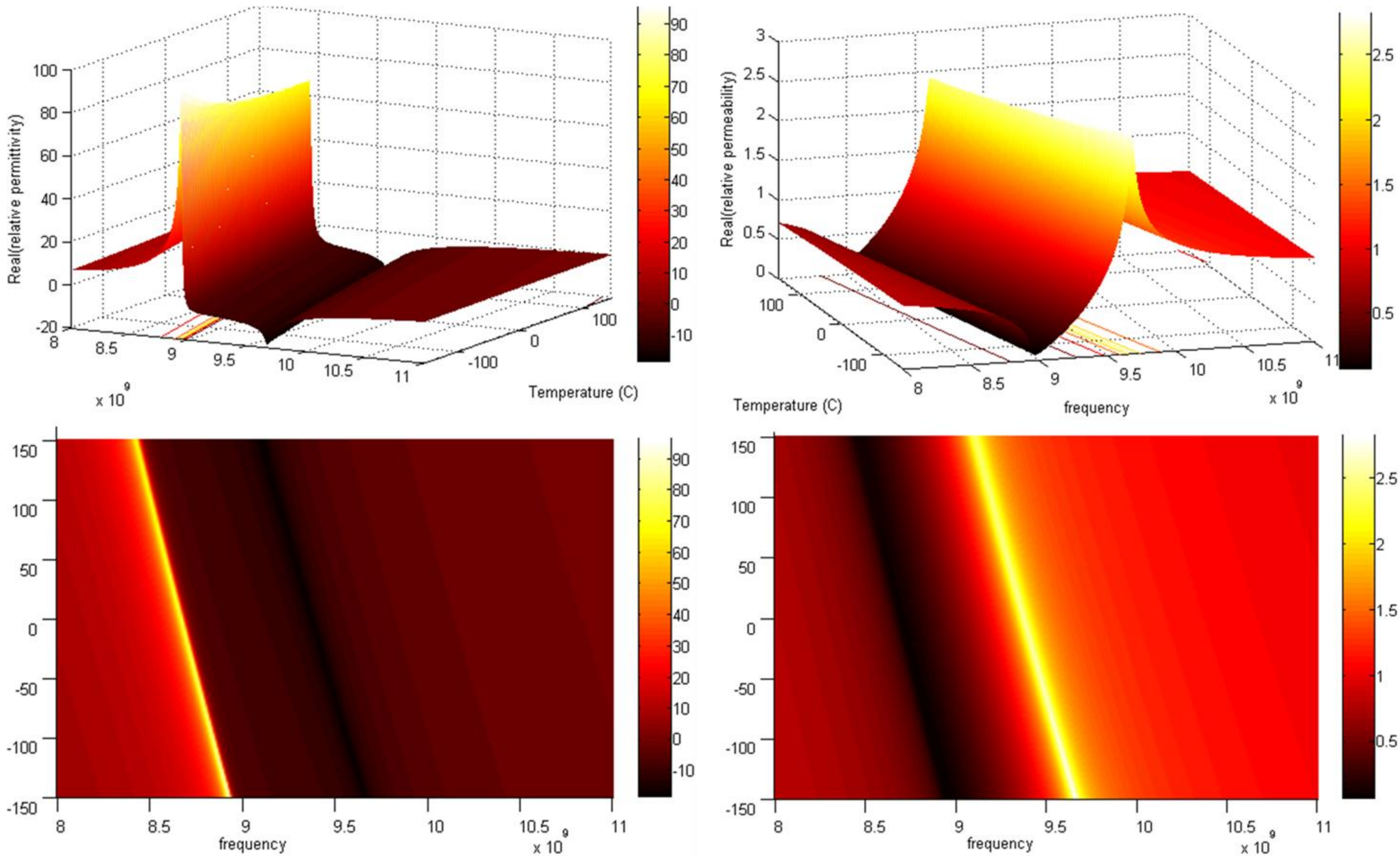
$$R = \frac{l}{\sigma A} \quad \mathrm{A} = \mathrm{b}\delta \quad \left(\delta = \sqrt{2/\omega_0 \mu \sigma}\right)$$

- **Utilized full wave simulation to assess parameter values at baseline condition**
  - **Expressions utilized to determine changes in value as a function of strain and temperature**
  - **Minimizes errors from inaccurate expressions**

Strain-Dependence

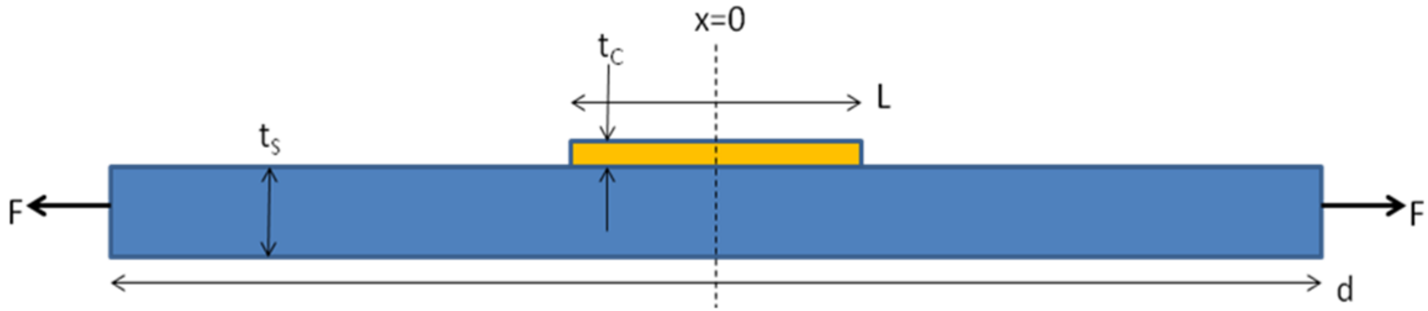


Temperature-Dependence



Low Modulus Substrates

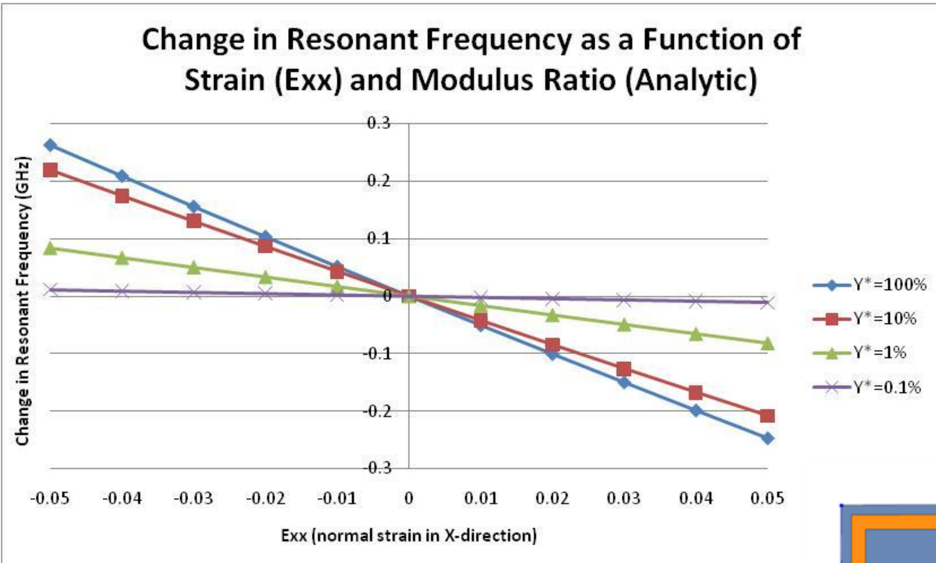
- **Previous analysis utilized thick, high-modulus substrates**
  - **Homogeneous Strain Profile**
  - **Simplified integration into analytic expressions**
- **A soft substrate complicates the strain profile**
  - **Utilize shear-lag models to describe the different strain levels in the copper and dielectric**
  - **Modifies geometry from previous equivalent circuit expressions**

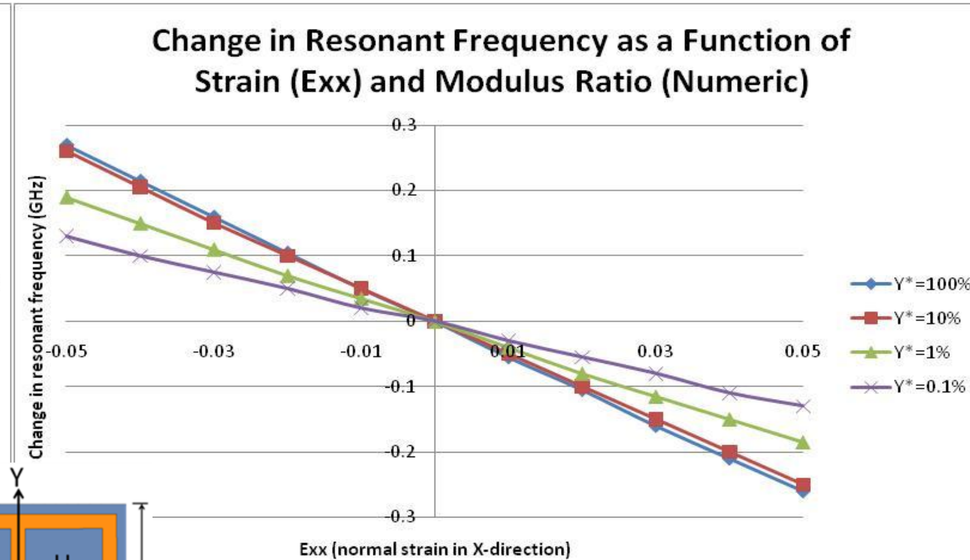


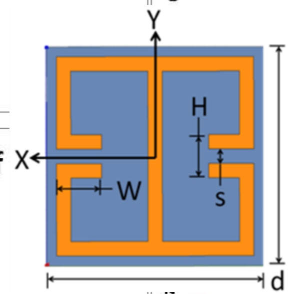
$$\in_{XXC} = \frac{\sigma_{XXC}}{Y_C} = \frac{E_{XX}}{Y_C}\left[{St_S Y_S}\Big/{t_C(1+S)} \right] = E_{XX}\left[\frac{Y^* t^*}{Y^* t^* + 1} \right]$$

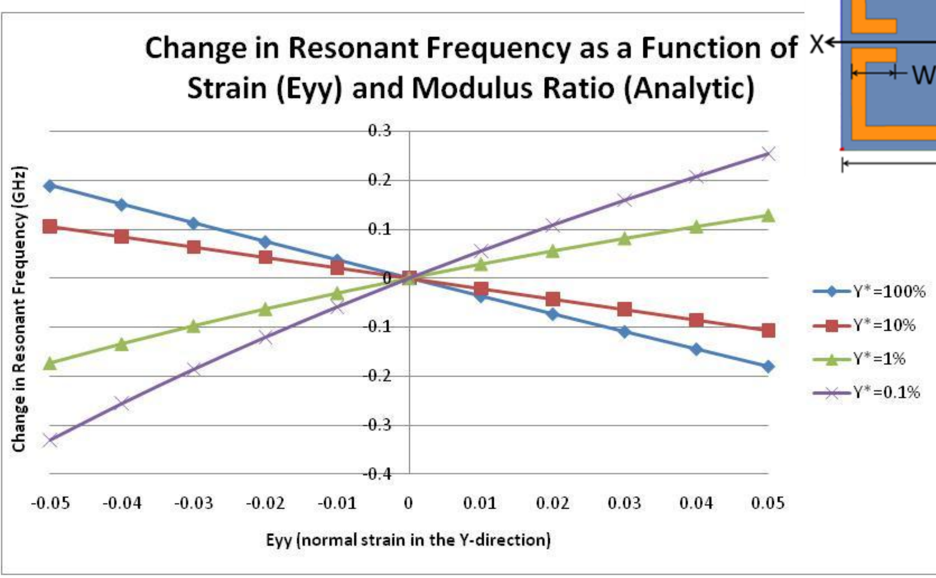
$$\in_{iiS} = \chi E_{ii} = \frac{d - l_c\beta}{d - l_c} E_{ii} = \frac{d - l_c\left(\frac{Y^* t^*}{Y^* t^* + 1}\right)}{d - l_c} E_{ii} = \frac{1 - \frac{l_c}{d}\left(\frac{Y^* t^*}{Y^* t^* + 1}\right)}{1 - \frac{l_c}{d}} E_{ii}$$

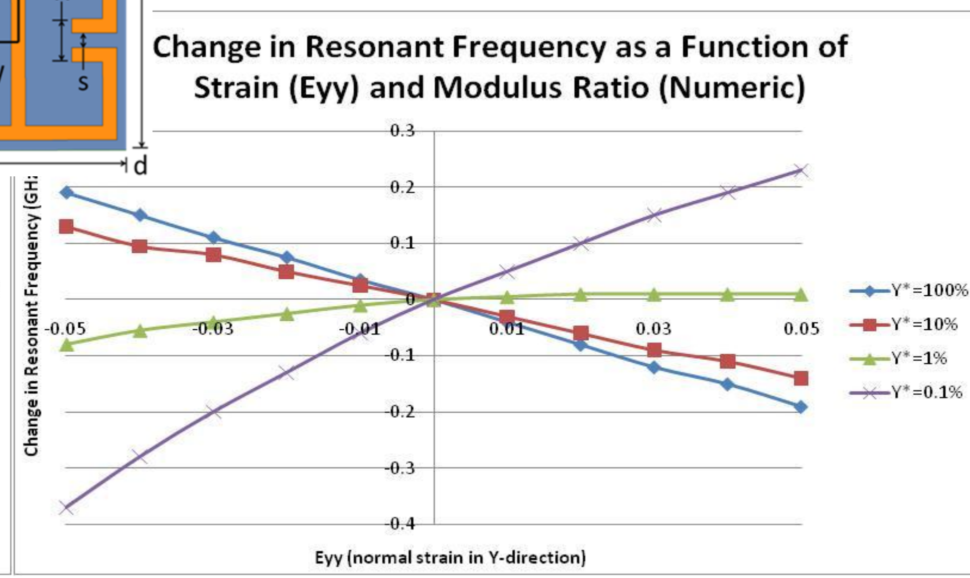
Low Modulus Substrate





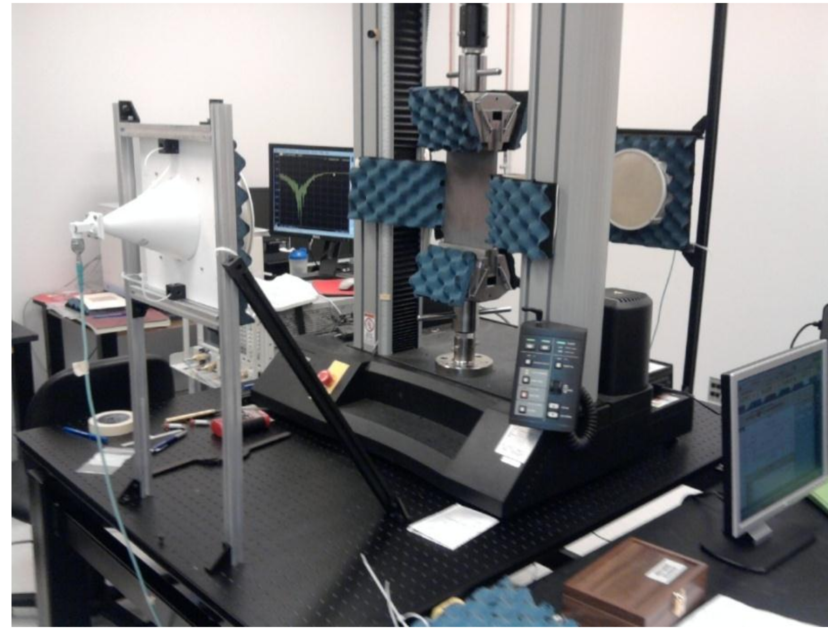


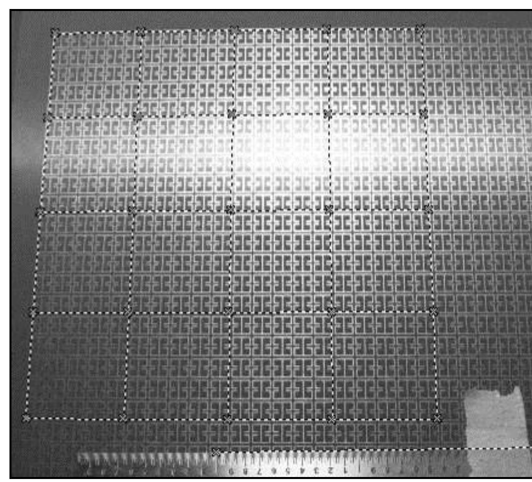


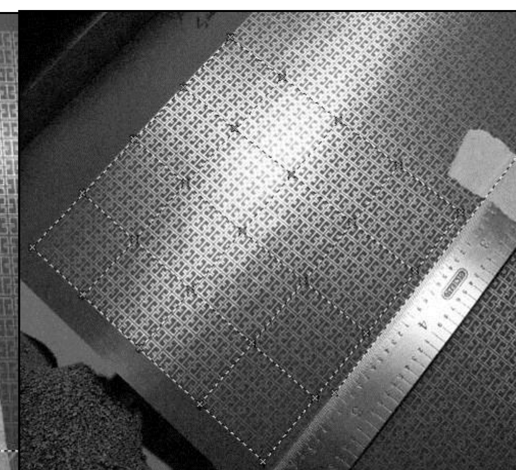


Testing

- **Facility at Duke University**
  - **Loadframe**
  - **RF Characterization**
- **Photogrammetry**
  - **Large area strain mapping**
- **Mechanical Characterization**
  - **At AFRL**
  - **Material Props did not meet vendor specifications**







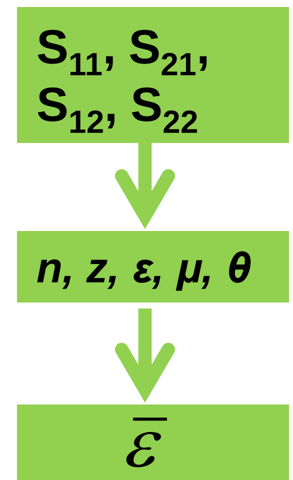
Test Results

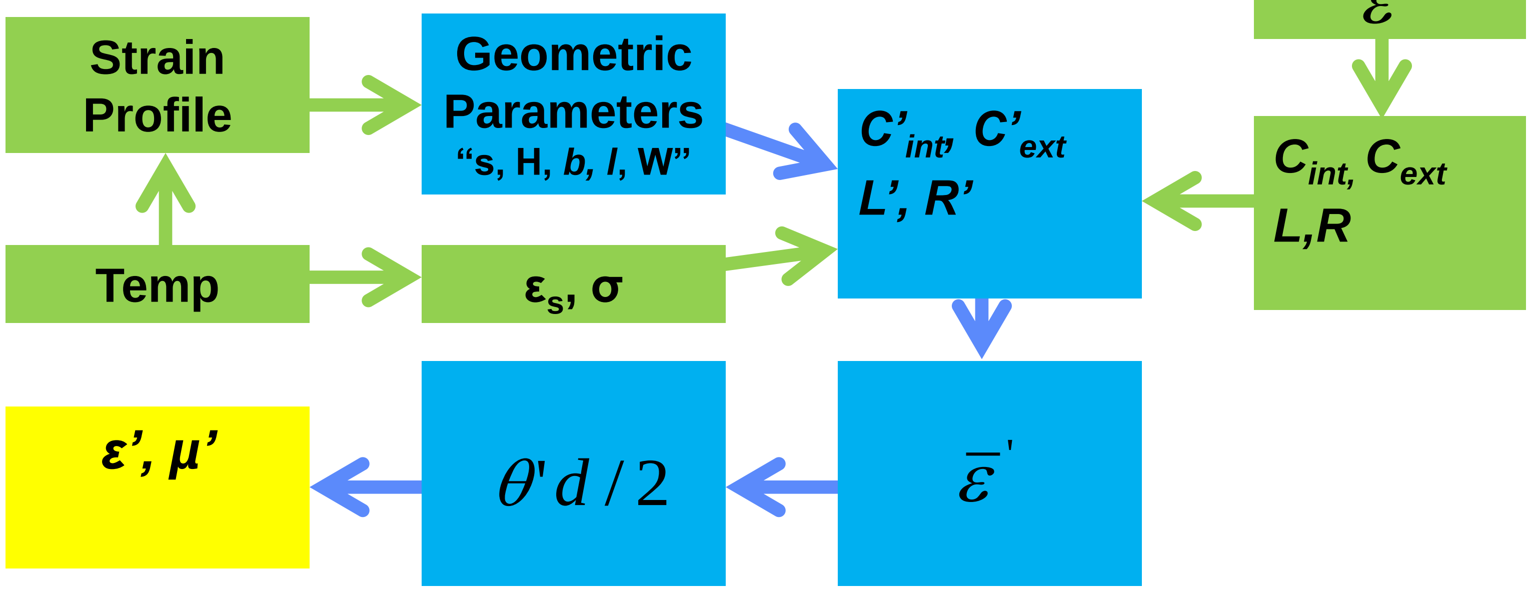
- **Predicted different shifts for the different samples**
- **Understanding EM performance requires knowledge of the full strain vector**

	Pyralux, ½oz Cu, Sample 1, 2400 lbs	Pyralux, ½oz Cu, Sample 2, 2400 lbs	Pyralux, 1oz Cu, Sample 1, 2400 lbs	Pyralux, 1oz Cu, Sample 2, 2400 lbs	5880, Sample 1, 1200 lbs	5880, Sample 1, 1600 lbs	5880, Sample 2, 1250 lbs
E_{XX} (%)	-1.12 to -1.06	-1.12 to -0.99	-1.25 to -1.19	-1.12 to -1.06	-0.73 to -0.59	-1.26 to -0.99	-0.79 to -0.66
E_{YY} (%)	4.16 to 4.3	4.03 to 4.1	3.76 to 3.96	4.03 to 4.1	1.10 to 1.14	1.83 to 1.87	1.10 to 1.14
Predicted Δf_0 (GHz)	**-0.032**	**-0.030**	**-0.020**	**-0.029**	**+0.009**	**+0.018**	**+0.012**
StDev Δf_0 (GHz)	0.002	0.003	0.002	0.001	0.006	0.003	0.003
Test Results (GHz)	**-0.039**	**-0.032**	**-0.026**	**-0.029**	**+0.011**	**+0.018**	**+0.013**

The Process

- **Baseline EM Parameters Extracted from Full-Wave Simulations**
- **Strain/Temp Profiles pulled from Finite Element Software**
- **Simple Scripts executed to determine EM Parameters at given strain/temp condition**





Conclusions

- Analytic Expressions are powerful tools for describing metamaterial strain/temp-dependence
  - Provide insight into physics behind linkage
  - Enable accurate prediction over the continuum of strains/temps
  - Rapid description of properties; >10^5 redux in model complexity
  - Rapidly predict strain/temp-dependence for unit cells in same design “family”
- Enable efficient determination of EM performance of large structures, with multiple unit cell designs, under complicated strain/temp profiles
- Care must be exercised in choosing appropriate analytic expressions
  - Circuit elements
  - Constitutive properties
- Process extendable to other unit cell designs
  - Magnetic metamaterials/SRRs
  - Owing to similar analytic expressions and circuit elements